AD-A181 169 INTERACTION OF ULTRASONIC WAVES WITH COMPOSITE PLATES (U) CINCINNATI UNIV OH DEPT OF AEROSPACE ENGINEERING AND ENGINEERING MECHANICS A H NAYFEH APR 87 1/1

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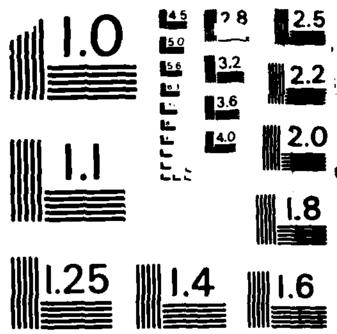

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ABSTRACT

During the first year of our reporting period we continued our close cooperation with the NDE Branch of the Materials Lab at Wright-Patterson Air Force Base. For our research part, we continued supplying analytical and computational methods on the modeling of the mechanical behavior of fibrous composites for applications in the NDE field. Specifically, we developed theoretical models to describe the influence of fibrous composite's microstructure (both in the forms of dispersive and anisotropic effects) and its gross behaviors. This was verified experimentally by using Leaky Wave propagation techniques whereas the scientific group at Wright Patterson continued conducting experimental verification of our modeling. These combined efforts contributed to an advancement of the state-of-the-art regarding the understanding for the ultimate good of developing inspection tools and methods to detect defects in such materials. As described below our efforts resulted in several presentations and publications in the open literature.

1. INTRODUCTION

The high specific strength and stiffness of composite materials have led to their wide spread use in efficient structures. Since most of these structures are subjected to cyclic loads which can lead to rapid degradation in load carrying capability, initial inspection and continued monitoring of these materials for detection and sizing of strength degrading flaws is necessary in order to ensure adequate structural reliability.

Unfortunately, many of the current inspection techniques cannot be directly utilized for this purpose because of the inhomogeneous, anisotropic nature of composites. Ultrasonic nondestructive evaluation is one useful means to insure the structural integrity of fibrous composites. In order to take full advantage of the information contained in an ultrasonic test [1], it is helpful to have a clear understanding of wave propagation characteristics in the material under examination.

Since it is clearly not practical to attempt a solution of the completely general elastic-wave problem, most prior work [2-5] has employed various approximations to render the calculations tractable. Our own approach [6,7] to interacting continua offers an alternative procedure for modeling the response of composites, where in particular, a rational construction of mixture momentum and constitutive-relation integration terms is given. This theory leads to simple wave propagation equations which potentially contain the full influence of the microstructure, that is, the distribution of displacements and stresses within individual constituents of the composite.

Under our ongoing research, in a recent paper [8] we presented results of theoretical calculations and experimental measurements of ultrasonic plate wave propagation in fiber-reinforced, unidirectional composite laminates. With the plate wave vector oriented parallel to the fiber direction, dispersion curves of phase velocity versus frequency and plate thickness have been constructed from fluid-loaded glass-epoxy composite plates.

The analytical models are supported by experimental results of plate wave propagation in the composite. The model begins with an approximate calculation of the effective homogeneous transversely isotropic elastic behavior of a unidirectional composite laminate in the long wavelength limit, using a two-step procedure based on alternating layered media. This intermediate continuum result is then incorporated into a calculation of the ultrasonic reflection coefficient of a fluid-loaded anistropic plate, which is assumed to approximate the fibrous composite laminate.

More recently we extend our analysis to the case in which the fibers are assumed to be anisotropic. Specifically, we treat the case which exhibits transverse isotropy in the direction normal to fiber direction. Results for isotropic fibers can also be obtained as special cases. Important composite examples which exhibits such property are the unidirectionally graphite-epoxy, ceramics and metal matrix composites. In order to derive the effective composite properties we shall extend the analytical procedure outlined in [8]. Results of this model have been compared with concurrently acquired experimental data.

2. THEORETICAL SUMMARY

We consider the case of an acoustic wave incident on a fiber-reinforced composite plate which is immersed in a fluid (schematically shown in Figure 1). In practice, the plate consists of small, nearly parallel transversely isotropic fibers of circular cross section laid out on an approximately hexagonal array as illustrated in figure 2a. A coordinate system is chosen such that the x axis coincides with the average fiber direction and that the z axis is normal to the plate-fluid boundaries. We further assume that the plate has infinite extent in the y direction. The plan is to approximate the highly structured composite by a continuum, retaining the appropriate elastic anisotropy, and to analyze the ultrasonic reflection from such a plate to study the behavior of plate waves in these materials.

We now follow the procedure of [8] and employ a building-block approach to arrive at the two-dimensional results we seek. First, a layered structure composed of fiber and matrix is analyzed, deriving from this parallel-stress model the properties of "compound" layer 1 of figure 2b. In the second step, the final model for the fibrous composite is established by treating the composite as consisting of the two-dimensional "compound" layer 1 stacked in series with the (matrix) layer 2 (see [8], for details).

Layered Model

Consider the bilayered composite of Fig. 3, composed of two types of laminates in welded contact and stacked normal to the y direction. The

translational invariance of the problem permits us to isolate the repeating unit (bounded by the two centerlines), as indicated in Fig. 3. On this cell all continuity and symmetry relations are displayed. The relevant equations of motion are given by

$$\frac{\partial \sigma_{ij}}{\partial r_i} = \rho \ddot{\nu}_j \ , \ i,j = 1,2,3 \tag{1}$$

which apply for each constituent. The appropriate constitutive relation for the isotropic matrix is given by

$$\sigma_{jk} = \lambda \delta_{jk} \frac{\partial \nu_\ell}{\partial r_\ell} + \mu\left(\frac{\partial \nu_j}{\partial r_k} + \frac{\partial \nu_k}{\partial r_j}\right), \tag{2}$$

and for the transversely isotropic fibers by

$$\sigma_{ij} = F_{ijk\ell} e_{k\ell} \ , \ i,j,k,\ell = 1,2,3 \tag{3}$$

where appropriate restrictions on the elastic properties $F_{ijk\ell}$ to reflect transverse isotropy are assumed. In equations (1), (2) and (3) summation over repeated variable indices in the same term is assumed. ν_i are the components of the displacement u,v,w; r_i are the spatial coordinates x,y,z; and σ_{jk} are the elements of the elastic stress tensor; the material density is ρ, and λ and μ are the Lame constants for the isotropic material. Following [8], applying the boundary conditions of Fig. 3 and averaging Eqs. (1-3) across the cell thickness according to $\overline{(\ )}_\alpha = h_\alpha^{-1} \int_0^{h_\alpha} (\ )_\alpha \, dy (\alpha = 1,2)$, followed by invoking the low frequency approximation (i.e. $\bar{u}_1 + \bar{u}_2 = \bar{u}$ and $\bar{w}_1 + \bar{w}_2 = \bar{w}$, $\bar{\sigma}_{yy1} = \bar{\sigma}_{yy2}$) leads to the effective two-dimensional description of the layered composite

$$\rho_c \frac{\partial^2 \bar{u}}{\partial t^2} = \frac{\partial \bar{\sigma}_{xx}}{\partial x} + \frac{\partial \bar{\sigma}_{xz}}{\partial z} \tag{4}$$

$$\rho_c \frac{\partial^2 \bar{w}}{\partial t^2} = \frac{\partial \bar{\sigma}_{zz}}{\partial z} + \frac{\partial \bar{\sigma}_{xz}}{\partial x} \tag{5}$$

$$\bar{\sigma}_{xx} = E_c \frac{\partial \bar{u}}{\partial x} + \lambda_c \frac{\partial \bar{w}}{\partial z} \tag{7}$$

$$\bar{\sigma}_{xz} = \mu_c (\frac{\partial \bar{w}}{\partial x} + \frac{\partial \bar{u}}{\partial z}) \tag{8}$$

where

$$E_c = F_{11} n_1 + E_2 n_2 - (\lambda_2 - F_{12})^2 / G \tag{9a}$$

$$\lambda_c = F_{12} n_1 + \lambda_2 n_2 - (\lambda_2 - F_{12})(\lambda_2 - F_{23}) / G \tag{9b}$$

$$\bar{E}_c = F_{22} n_1 + E_2 n_2 - (\lambda_2 - F_{23})^2 / G \tag{9c}$$

$$G = \frac{F_{22}}{n_1} + \frac{E_2}{n_2} , \; E_2 = \lambda_2 + 2\mu_2 , \tag{9d}$$

and ρ_c and $\bar{\sigma}_{ij}$, $i, j = x,z$ are the weighted sums of the respective quantities for materials 1 and 2, e.g.

$$\rho_c = \rho_1 n_1 + \rho_2 n_2 , \; \bar{\sigma}_{ij} = n_1 (\bar{\sigma}_{ij})_1 + n_2 (\bar{\sigma}_{ij})_2 \tag{10a}$$

with $n_\alpha = h_\alpha / (h_1 + h_2)$ being the volume fraction of materials 1 and 2 in the laminated plates model. Furthermore, F_{11}, F_{12}, F_{22} and F_{23} stand for F_{1111}, F_{1122}, F_{2222} and F_{2233}, respectively.

Fibrous Model:

Building on the above calculation we now construct the effective elastic properties for a fibrous composite by considering the "compound" layer 1 stacked in series with the matrix material of layer 2 normal to the z axis. Similar to the procedure of [8] by following the development that led to Eqs. (6), (7) and (8), we define new elastic constants appropriate to mixtures in parallel and series of the properties of compound layer 1 and matrix layer 2. These relations take the series combination form

$$\rho = \rho_c n_c + \rho_2 n_2^* , \quad E = E_c n_c + E_2 n_2^* \tag{11}$$

and the parallel combination form

$$E^* = \bar{E}_c E_2/(\bar{E}_c n_2^* + \mu_2 n_c) , \quad \mu^* = \mu_c \mu_2/(\mu_c n_2^* + \mu_2 n_c) , \tag{12}$$

whereas

$$\lambda^* = (\lambda_c n_c/E_c + \lambda_2 n_2^*/E_2)(n_c/\bar{E}_c + n_2^*/E_2)^{-1} . \tag{13}$$

Here n_c is the volume fraction of the compound layer and n_2^* is that of the matrix layer (see [8]). Now a new set of two-dimensional field equations can be constructed which are formally identical to Eqs. (1), (or equations (4) and (5) with ρ_c of (5a) replaced by ρ of (11a), but where instead of Eqs. (6), (7) and (8) we have the mixture constitutive relations

$$\sigma_{xx} = E \frac{\partial \bar{u}}{\partial x} + \lambda^* \frac{\partial \bar{w}}{\partial z} , \quad \sigma_{zz} = E^* \frac{\partial \bar{w}}{\partial z} + \lambda^* \frac{\partial \bar{u}}{\partial x} \tag{14a,b}$$

$$\sigma_{xz} = \mu^* \left(\frac{\partial \bar{u}}{\partial z} + \frac{\partial \bar{w}}{\partial x}\right) . \tag{14c}$$

3. DERIVATION OF REFLECTION COEFFICIENT

Consider the fibrous composite modeled above to be in the form of a plate of thickness d and immersed in an infinite fluid medium. The upper and lower surfaces of the plate are situated at $z = 0$ and $z = d$, and an incident harmonic sound wave propagating in the x-z plate insonifies the plate. The incident wave vector k_f makes an angle θ with the z axis, and all particle motion is assumed to be confined to the x-z plane. The calculation of the plane-wave reflection coefficient from a fluid-loaded, transversely isotropic plate proceeds in a straightforward manner. Substitution of the constitutive relations of Eqs. (14) into the equations of motion Eqs. (4) and (5) (with ρ_c replaced by ρ) yields coupled, second-order partial differential equations for the displacements. Making the usual ansatz for the formal solutions leads to a system of linear simultaneous equations for the displacement amplitudes. By solving these equations and, after applying rather lengthy algebraic reductions and manipulations, we derive the following expressions for the reflection and the transmission coefficients

$$R = \frac{AS - Y^2}{(S + iY)(A - iY)}, \tag{15}$$

$$T = \frac{-iY(S + A)}{(S + iY)(A - iY)}, \tag{16}$$

where

$$S = \alpha_f[K_1P_2 \cot(\alpha_2\xi \frac{d}{2}) - K_2P_1 \cot(\alpha_1\xi \frac{d}{2})] \tag{17a}$$

$$A = \rho_f[K_1P_2 \tan(\alpha_2\xi \frac{d}{2}) - K_2P_1 \tan(\alpha_1\xi \frac{d}{2}] \tag{17b}$$

$$Y = \rho_f c^2(K_1W_2 - K_2W_1) \tag{17c}$$

$$\alpha_f^2 = \frac{c^2}{c_f^2} - 1 \tag{17d}$$

$$K_j = W_j + \alpha_j \ , \quad P_j = \lambda^* + E^* W_j \alpha_j \tag{17e}$$

$$W_j = (\rho c^2 - E - \alpha_j^2 \mu^*)/[(\lambda^* + u^*)\alpha_j \ , \ j = 1,2 \tag{17f}$$

and α_j are the solutions of the quartic equation

$$(E - \rho^2)(\mu^* - \rho c^2) + [(E - \rho c^2) + [(E - \rho c^2)E^*$$

$$+ (\mu^* - \rho c^2)\mu^* - (\lambda^* + u^*)^2]\alpha^2 + E^* \mu^* \alpha^4 = 0 \ . \tag{17g}$$

In the above expressions c, c_f, ρ_f and ξ are the phase velocity, fluid wave speed, fluid density and wave number, respectively.

In the absence of the fluid, i.e., for $\rho_f = 0$, the denominators of equation (15) and (16) reduce to the characteristic equation for the propagation of free (Lamb) waves in the plate. For isotropic materials the Lamb characteristic equation has been investigated extensively in the literature [9]. In the presence of the fluid, however, very little discussion or numerical investigation exists. Schoch [9] pointed out, while investigating isotropic plates, that the condition for total transmission, if the presence of the fluid is neglected, coincides with the existence of Lamb modes. Following Schoch's arguments, the total transmission condition in the presence of the fluid for the present case is given by (see equation (15))

$$SA - Y^2 = 0 \tag{18}$$

This characteristic equation defines the frequency dependence of the phase velocity of total transmission. As will be shown later on in the numerical

discussions dispersion results obtained from these correlate very well with experimental data. Accordingly, the condition (18) which yields Lamb like dispersion curves should not be termed strictly Lamb's condition characteristic equation. Furthermore, this condition certainly does not satisfy the free plate characteristic equation

$$(S + iY)(A - iY) = 0 \quad . \tag{20}$$

4. RESULTS AND DISCUSSION

For our illustrations we first choose a graphite-epoxy composite where fibers are transversely isotropic.

Using the total transmission identification criteria, we constructed the spectrum of dispersion curves shown in figure 4. Also displayed on this curve are the extensive experimental data. As may be seen excellent comparison is obtained. Furthermore, both the experiments and the analysis display the rather unusual behavior shown at the lower frequency ranges in the vicinity of the lowest order modes. Pitts, et al [12] have noted some disparity between solutions of the characteristic equation and the zeros of the reflection coefficient of the two fundamental modes for an isotropic plate in a fluid.

The left running branch of this curve approaches the fluid wave speed as $fd \to 0$. By arbitrarily reducing the fluid density, we have shown numerically that the dispersion relaxes to the Lamb wave case in an anisotropic plate, i.e. the total curve splits into two curves which are identifiable with the antisymmetric and symmetric fundamental free (Lamb) modes. In fact, both modes converge to the surface wave speed as $fd \to \infty$, as expected. In the absence of the fluid the "vertical" branch of the curve can be identified with the zeroth symmetric mode. From this pronounced curving effect we have been able to verify numerically the existence of this phenomenon for several isotropic materials such as steel, aluminum and copper. Here the effect is extremely small [12] and has not been demonstrated experimentally.

In figures 5 and 6 we attempted to compare our analytical and experimental results using the same total transmission criteria for a Nicalon-BMAS ceramic composite and for a graphite-aluminum metal matrix composite. Due to the lack of complete and accurate elastic properties for each composite constituent we were unable to construct all of the required effective properties needed for our calculations. In the absence of the shear modulas of the ceramic matrix, for example, we have estimated this property from the experiment which led to the required properties listed in [10]. Using these properties we were able to well fit the data as is seen from figure 5.

In the case of the graphite-aluminum composite sample not all of the elastic constants are known. This type of graphite fiber, Union Carbide P-100, has not been as well characterized as the Thornal T-300 used in the graphite-epoxy sample. Accordingly, we adjusted the effective normal extensional elastic constant E^* and used the properties listed in [10] to generate the comparison in figure 6. The fact that with these adjusted parameters, we are able to well compare all the modes shows the consistency in both the theoretical and experimental investigation.

5. SUMMARY

The mechanical behavior of fiber-reinforced composites has been investigated theoretically and experimentally. The theoretical model, based on a continuum mixture approach, replaces the actual composite by a homogenized, transversely isotropic medium. Although the model can accommodate geometric dispersion arising from the finite fiber diameter, calculations have been particularized to the long wavelength limit. In this case all the dispersive behavior is due to the finite plate dimensions. Based on this model, the transmission and reflection coefficients for a composite plate immersed in a fluid have been calculated in a 2-dimensional geometry. By examining total transmission, the existence of propagating modes in the plate has been identified. Numerical results of the plate wave dispersion are presented for a variety of advanced ceramic and metal-matrix composite materials. Concurrent with this analysis we have performed

experimental measurements on a ceramic composite plate of Nicalon-BMAS. While excellent agreement is achieved with our earlier results on well characterized material combinations, such as glass-epoxy or graphite-epoxy, preliminary comparison of the ceramic composite data with the model calculation suggests a lack of complete information on the elastic properties of the constituents.

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10. Graphite-Epoxy: $E = 155.6$, $E^* = 15.95$, $\lambda^* = 3.72$, $\mu^* = 6.36$ GPa, $\rho = 1.69/cm^3$

    Ceramic: $E = 175$, $E^* = 170$, $\lambda^* = 55.63$, $\mu^* = 17$GPa, $\rho = 2.62g/cm^3$

Graphite-Aluminum: $E = 358$, $E^* = 102.6$, $\lambda^* = 30$, $\mu^* = 36$ GPa,

$\rho = 2.55 g/cm^3$.

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7. Publications of Research Sponsored by This Grant

Several publications comprising extensive comparisons between our theoretical and numerical model and the experimental results of Dr. D. Chimenti at the Material Laboratory have resulted. These include:

(1) D.E. Chimenti and A.H. Nayfeh, "Anomalous Ultrasonic Dispersion in Fluid-Coupled, Fibrous Composite Plates" Applied Physics letters, 49(a), September 1986.

(2) A.H. Nayfeh and D.E. Chimenti, "Continuum Modeling of Ultrasonic Behavior in Fluid-Loaded Fibrous Composite Media," proceedings of the review of progress in Quantitative NDE, La Jolla, California 3-8, August 1986.

(3) D.E. Chimenti and A.H. Nayfeh, "Ultrasonic Dispersion in Fluid-Coupled, Graphite-Epoxy Composite Plates," proceedings of the Review of progress in Quantitative NDE, La Jolla, California, 3-8, Aug. 1986.

(4) A.H. Nayfeh, "Acoustic Wave Reflection from Water/Laminated Composite Interfaces," proceedings of the Review of Progress in Quantitative NDE, La Jolla, California, 3-8, Aug. 1986.

(5) A.N. Nayfeh and D.E. Chimenti, "Continuum Modeling of Ultrasonic Behavior in Fluid-Loaded Fibrous Composite Media with Applications to Ceramics and Metal Matrix Composites," proceedings of the Conference on Nondestructive Testing and Evaluation of Advanced Materials and Composite. Sponsored by Department of Defense, 19-21, Aug. 1986 at U.S. Air Force Academy, Colorado Springs, Colorado.

8. Presentations of Research Sponsored by this Grant

All the above quoted proceedings publications were presented at their respective conferences.

9. Abstracts Submitted for Publications During 1987

1. A.H. Nayfeh and T.W. Taylor, "Interaction of Ultrasonic Waves With Layered Media," To be presented at the Acousto-Ultrasonics: Theory and Application Conference, Blacksburg, VA, July 12-14, 1987.
2. A.H. Nayfeh and T.W. Taylor, "The Influence of Interfacial Conditions on the Ultrasonic Wave Interaction With Multilayered Media," to be presented at the Review of Progress in QNDE, Williamsburg, VA June 21-26, 1987.
3. D.E. Chimenti and A.H. Nayfeh, "Plate Mode Propagation in an Arbitrary Oriented Fibrous Composite Plate," to be presented at the Review of Progress in QNDE, Williamsburg, VA, June 21-26, 1987.

10. Work in Progress

We are now conducting research on two fronts; on the first we are now in the process of extending our results to the case where the fibers are directed in an arbitrary direction to the wave front. This problem is much more analytically involved and needs developing advanced tools to handle wave reflections from general anisotropic media. The concept of phase planes will be exploited to numerically define the propagation wave vectors for the plate. Results on this problem will be available for comparison with the concurrently acquired experimental data of Dr. Chimenti.

On the second front we have started modeling the interactions of multilayered fibrous composite plates with ultrasonic waves. Arbitrary numbers of plates constituents will be allowed. All appropriate interfacial conditions will be invoked. Furthermore, in order to simulate the existence of large cracks in the forms of debonding or delamination we plan to introduce a slip boundary condition. This condition does not require the continuity of shear stress and displacements along the interface. Thus the shear stresses on the interface will vanish and hence result in the weakening of the interface. This concept seems to be promising and will be verified experimentally in the near future.

11. Professional Personnel

The grant supports Mr. Timothy Taylor who is a graduate student in the Engineering Mechanics program of the Aerospace Department. He is working towards his MS degree and will be admitted to the PhD program next September.

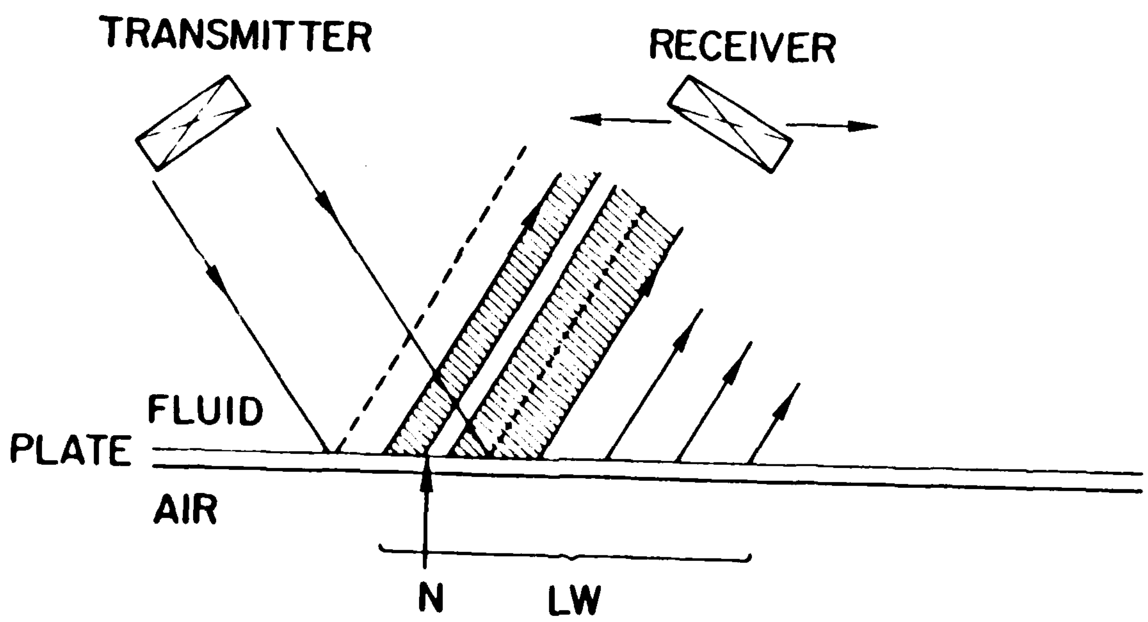

Figure 1. Schematic illustration of wave interaction with the composite plate.

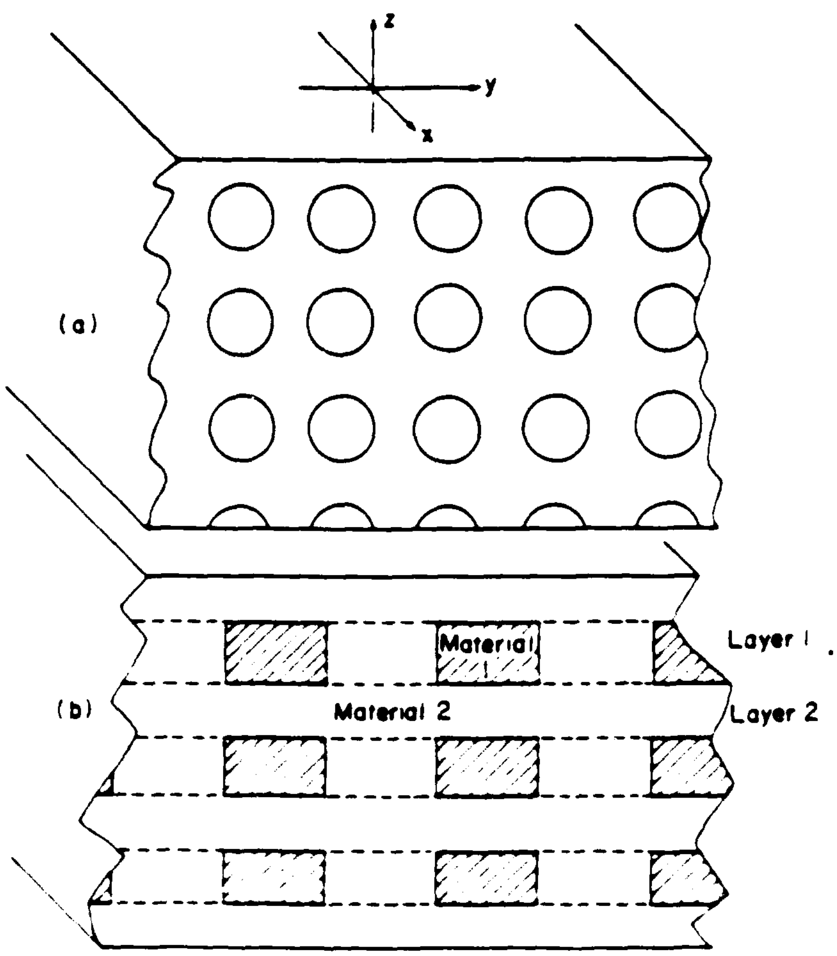

Figure 2. Schematic representation of a fibrous composite. Idealized actual composite is shown in (a); model composite upon which calculations are based is in (b). Layer 1 is a "compound" of fiber and matrix properties, whereas layer 2 includes only the matrix properties.

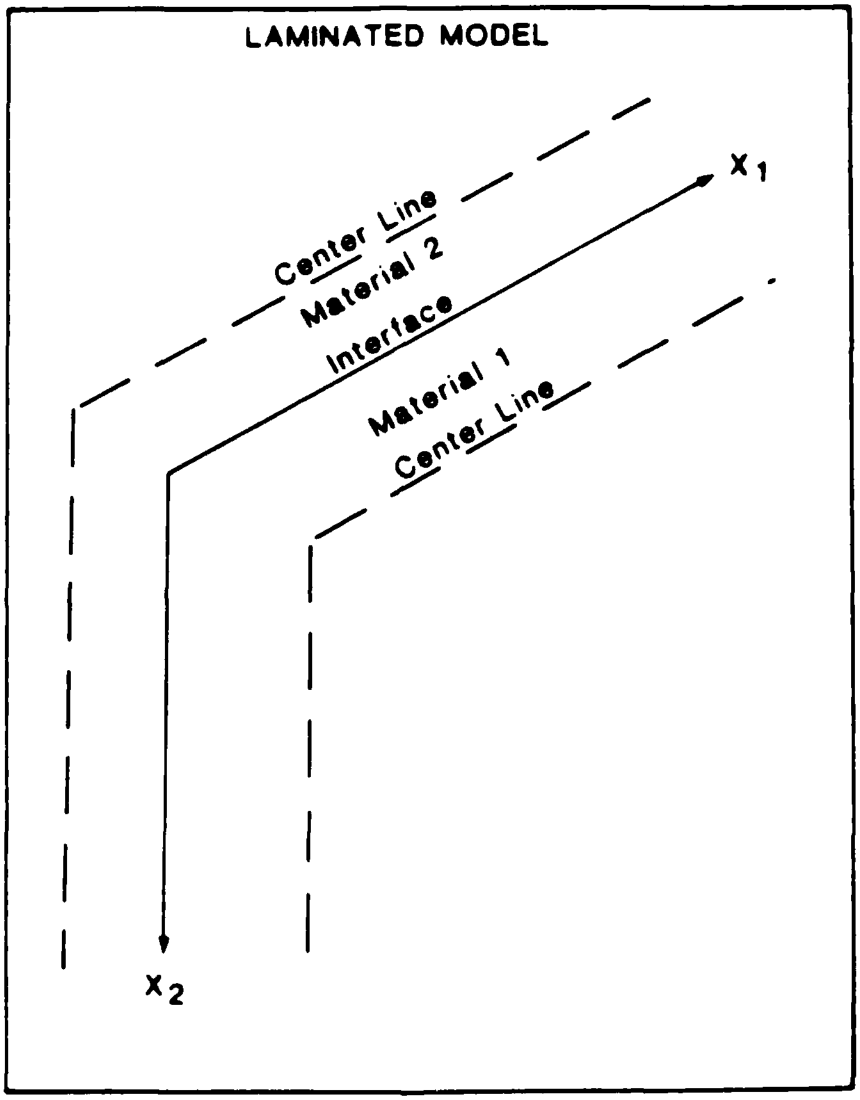

Figure 3. Geometry of laminated composite.

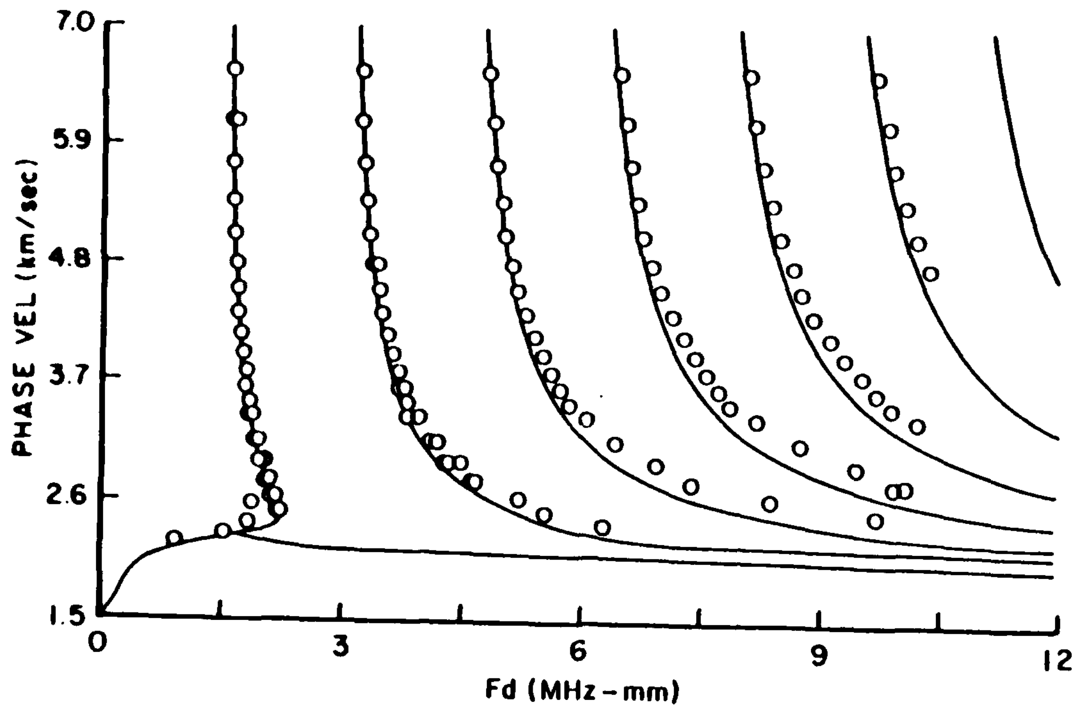

Figure 4. Total transmission dispersion for the graphite-epoxy plate; comparison between theory and experiment.

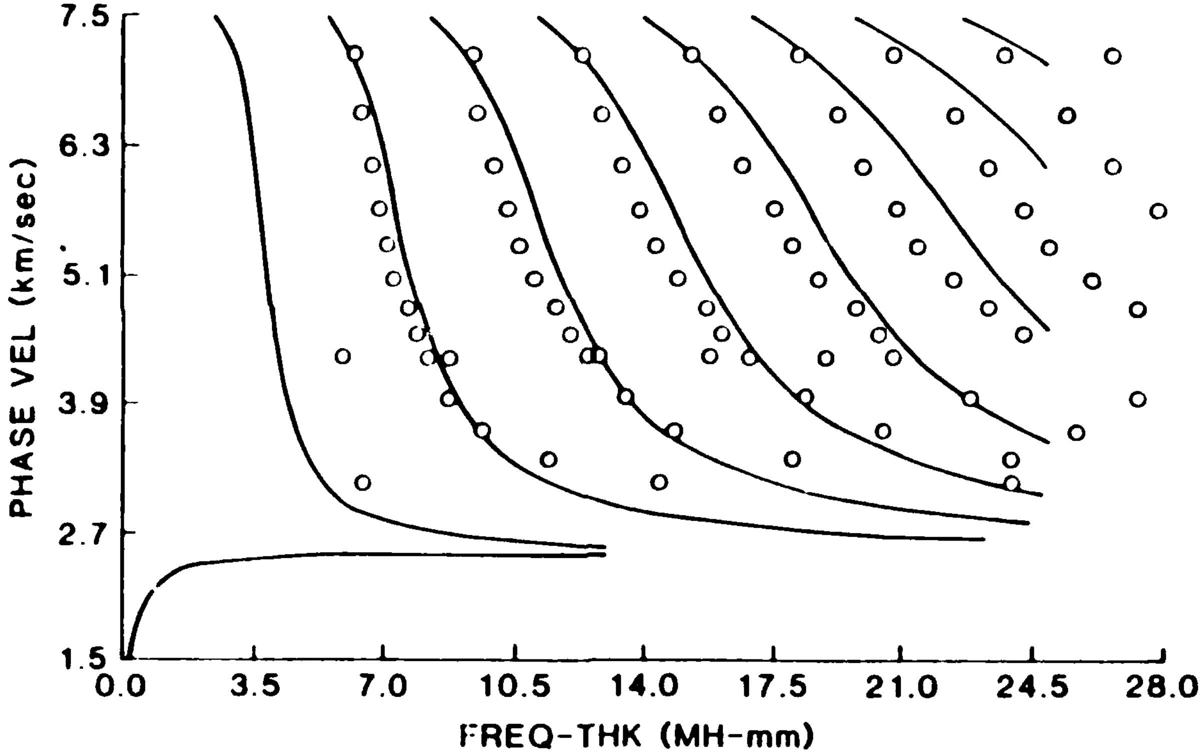

Figure 5. Total transmission dispersion for the ceramic plates; comparison between theory and experiment.

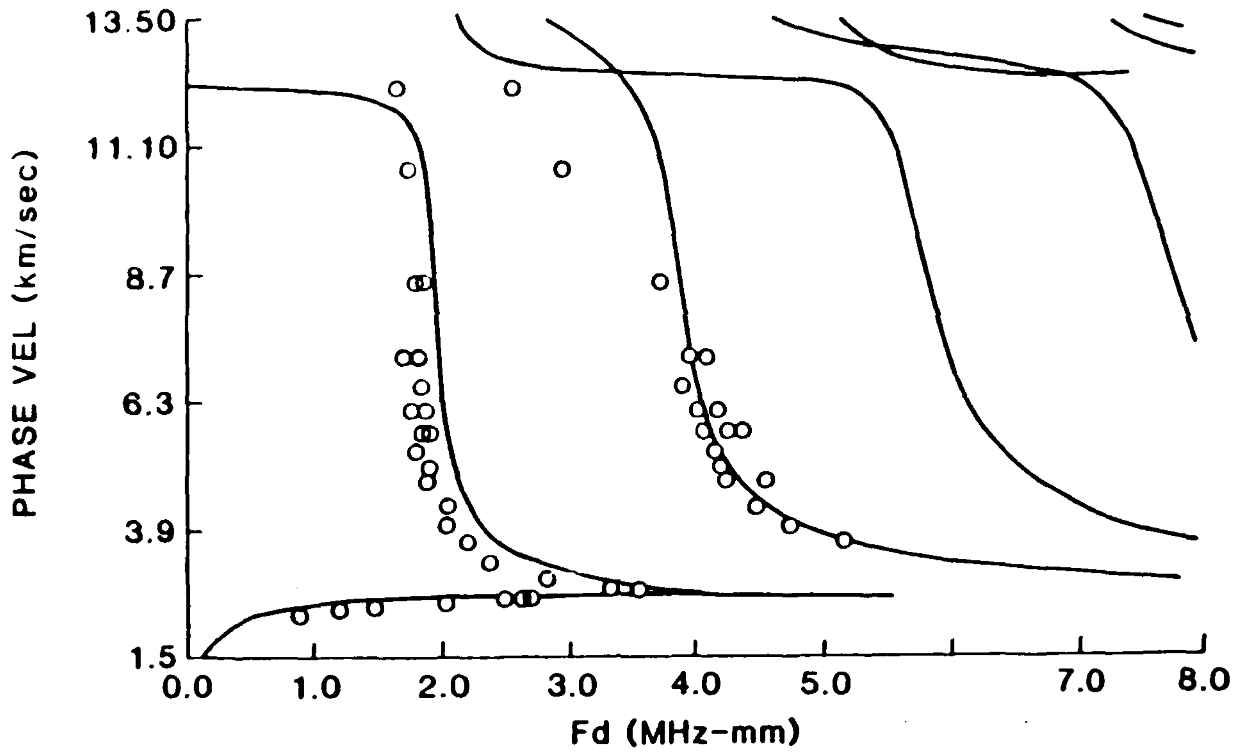

Figure 6. Total transmission dispersion for the graphite-aluminum plate; comparison between theory and experiment.

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